Exploring Time and Space: The Future of Space-based Astronomical Observatories

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Ever since Galileo pointed the first telescope at the night sky, the desire to further observe and understand the Universe has driven the construction of ever larger and more powerful telescopes. At the very beginning of the space age, scientists and engineers began envisioning the discoveries that could be made if a telescope were placed in space, above the turbulence and absorption of the atmosphere. The success of NASA's Great Observatories program has not only led to amazing discoveries but has left us with ever more questions and a desire to go deeper and see more. NASA's most famous observatory, the Hubble Space Telescope, has not only produced revolutionary astronomical discoveries, but has connected people to science as one of our greatest ambassadors. Telescopes capture our imagination because they are the ultimate vehicle for exploration, allowing us to explore not just the strange and beautiful structures in our universe – structures of a seemingly unfathomable scale at distances infeasible for physical human travel – but they allow us to explore our past, looking back in time billions of years. These observatories let us explore the ultimate questions: Where did we come from? How did we get here? Are we alone? For the past 19 years, NASA, ESA, CSA, and universities and engineering companies across the world have been developing the next-generation flagship space observatory, the James Webb Space Telescope (JWST). This telescope is so large it must be folded for launch, then deployed and aligned on its journey to its final orbit one million miles from Earth. It is the largest, most complex, and most audacious observatory built for space.

The Webb Telescope began taking conceptual shape in the decade after Hubble's launch and entered formal development in 2002. Optimized to answer the big questions of origins, JWST's fundamental mission to observe the first generation of stars and galaxies and study the early stages of star and planet formation directly lead to the architecture we see today. Light from the first generation of stars has been traveling through our expanding universe for billions of years, causing redshift that moves features used to determine object composition from the visible and UV into the infrared portion of the spectrum. Observing in the infrared has the added benefit of allowing the telescope to "see" through the opacity of the dusty stellar nurseries to the warm stars within to aid in the study of star and planet formation. For these reasons, JWST is optimized to observe in the infrared. Similarly, the desire to observe the vanishingly faint signals from the early universe and observe spectra from small exoplanet atmospheres, drove the need for the largest feasible collecting area to increase the observable signal. JWST boasts a 6.5m diameter primary mirror, near the largest that could feasibly be folded to fit within the largest rocket faring available when the program was architected at the turn of the 21st century.

Like any interesting engineering problem, it is the details that emerge when moving from basic architecture to operational design that are the key to success. The optical sensitivity requirements drove mirror quality and, because of the segmented design required to fold the primary mirror to fit in the Ariane V rocket faring, the positioning requirements for the actuator system used to align the 18 primary mirror segments to perform as a single mirror. This required the development of actuators that could position each mirror in six degrees of freedom to within 10 nanometers of the desired position and precisely control the radius of curvature of each mirror. The infrared wavelength requirement drives the need to cool the entire observatory to less than 50 Kelvin to avoid self-emission from a warm telescope dwarfing the faint mid-IR signals the observatory is designed to measure. Designing a telescope to operate at such cold temperatures, further led to design trades for stable materials, careful thermal design, sunshade materials to reject heat and passively cool the telescope, large radiators, and the development of electronics that can not only survive, but operate at cryogenic temperatures.

In total, building the Webb Telescope required development of ten new technologies and many design and manufacturing firsts. This was an un-precedented level of technology development for a space asset that cannot be serviced in its orbital location at Earth-Sun L2, one million miles from Earth. In addition to specific new component technologies, building an observatory of this size that must be folded for launch and then reconstructed in space, created significant challenges to the traditional test-as-you-fly approach used to ensure performance of space assets prior to launch. Testing a telescope of this size, designed to meet requirements in zero-g, zero atmosphere, and at 50 Kelvin, in a way that directly demonstrates the extreme sensitivity required to meet the science requirements, was both technically, logistically, and cost prohibitive. This necessitated development of novel test and analysis approaches that will serve as a proof of concept and pathfinder for approaches to ground verification that will be required should we one day make a telescope too large to fully assemble on the ground before launch.

The engineering challenges overcome to construct this marvel of scientific instrumentation will enable discoveries that drive the next decade of astronomy and demonstrate the technological and programmatic building blocks required to continue to push the state of the possible. While we look forward to launch of the Webb Telescope later this year, plans are already under way for future generations of space observatories. New concepts involve making telescopes even larger, more stable, or colder to allow astronomers to see further back in time, better understand galaxy evolution, or probe the likelihood of extra-solar life and even image Earth 2.0. For the past several years, four potential future flagship-class space observatories have been undergoing early architecture studies. All of these concepts involve large-scale optics and other new instrumentation technologies to further study our Universe. While scientists and engineers are eagerly awaiting the recommendation of the Astro2020 Decadal survey, which has reviewed each concept to consider its scientific relevance and technological achievability, the technology available to us today is already leading us to dream even bigger.

In aerospace, we often talk about the “tyranny of the faring”; we are limited by the mass and volume constraints of existing rockets. The observatories in review by the decadal panels take advantage of the newest generation of extremely large rockets. But ultimately even these have limits. Beyond limiting volume, mass constraints lead to long design cycles and careful architecture and material selection to minimize mass while still ensuring the structure can survive launch, driving the cost and time to orbit. But what if we weren’t limited by a single launch? We have already demonstrated in-space assembly and servicing, albeit not to the precision and stability of an astrophysics observatory. Design techniques developed for JWST allowed structure assembly to fairly loose mechanical assembly tolerances while still being capable of aligning mirror segments and optical elements to extreme precision. When we can design solely for on-orbit stability rather than launch, the design space can open further. NASA’s in-Space Assembled Telescope (iSAT) study showed the feasibility of a multi-launch, robotically assembled telescope with an aperture of 20m. This is surely not an upper limit, and some have proposed evolvable telescopes that that can be grown over time, self-assembling telescopes of many small, single-mirror spacecraft with the secondary flying in formation to reflect the light to the instruments, along with even more exotic designs. The technology to take this next step, to break the tyranny of the faring to enable a truly unprecedented discovery, is available today – all that is required is the investment and will to undertake such an ambitious endeavor.